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ONR Final Report: ONR N-00014-90-J-4014-P01
Tactile Sensing and Control in Humans and Robotic/Teleoperated Systems

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August 4, 1992

Summary

Over the last several years, a number of sophisticated robot hands have been developed for laboratory use. However, while such hands approximate the mechanical complexity of human hands, their application in manipulation tasks remains in a primitive stage. Unlike human hands, they rely on minutely programmed task descriptions that are time-consuming to generate and susceptible to unanticipated changes in the task or the immediate environment. This is largely because they cannot use tactile information to detect and respond to changes in an event-driven fashion as humans do. Similarly, teleoperated manipulation systems are slow and difficult to use because the operator does not receive appropriate tactile feedback from the manipulator.

Accordingly, the work described is aimed at advancing our basic understanding of how to acquire, interpret and respond to tactile information and at advancing the state of the art in tactile sensing and information processing for robotic and teleoperated systems. The work involves the development of models of sensor/skin/contact dynamics, algorithms for interpretation of tactile information and control strategies for responding to tactile events. A set of parallel experiments with human subjects and robotic manipulators was performed to evaluate and refine the models and algorithms. Continued collaboration among Cutkosky, Howe and Johansson under a new U.R.I. grant will permit us to expand the scope of that work to include the development of new tactile sensors integrated with information processing hardware and software.

Significant Accomplishments

The most significant result of the Stanford/Harvard/Umea collaboration is a promising new approach to grasp force control in manipulation with robots and teleoperators. Experiments at Umea showed that human subjects control grasp forces and apply manipulation strategies using information from fast-acting (FAI and FAII) tactile afferents which signal events such as the onset of slipping between the fingers and a grasped object. An information exchange between Umea and Stanford led to experiments that demonstrated that the output of these FAI and FAII sensors is occasionally accompanied by small, but detectable, redistributions in the tangential contact forces between the fingertips of the human subjects and the objects that they were grasping.

Dynamic tactile sensors, specifically the skin acceleration and the stress rate sensors, were developed at Stanford for robotic and teleoperated hands to provide information similar to the human FA sensors. Triggering off the "microslip" information provided by these sensors, a manipulator's force control algorithm can then quickly adjust the grasp force so that no gross sliding occurs. Using such an approach, it is possible for a robot to maintain control of the grasped object, using the minimum necessary grasp force to prevent slipping. Work at Harvard extended this approach to teleoperated master/slave devices. A tactile display was built that induces small redistributions in the tangential forces at the operator's fingertips when a skin acceleration sensor at the slave end detects that the remotely grasped object is about to slip. In trials with human operators at Harvard and Umea, the tactile display was found to consistently trigger increases in grasp force and stiffness that were comparable to normal human responses to the onset of slipping.

The significance of the new grasp force control approach is that for the first time, both robots and human operators can receive reliable information about the onset of slipping at the end effector and can take appropriate action. This allows delicate objects to be handled without excessive grasp forces. This work advances the basic understanding of how to acquire, interpret and respond to tactile information and has advanced the state of the art in tactile sensing and information processing for robotic and teleoperated systems.

Experiments

The results summarized above are discussed in more detail in this section and fall into the following areas:

- Exchange of information between physiology and robotics
- Dynamic tactile sensing for robotic grasp force control
- Dynamic tactile sensing for grasp force control with teleoperated equipment
- Tactile sensor development
- Control systems development

Exchange of information between physiology and robotics

An intensive information exchange and some preliminary experiments took place during a visit by Cutkosky and Howe to Umea during August 14 – 18, 1990. Details are summarized in [Cutkosky 1990a]. Some points that led to subsequent experiments were as follows:

1. There are a number of reflexes which suggest that people may control internal and external grasp forces independently, as is currently the favored approach in the robotics literature on dextrous manipulation.

2. When subjects grasped objects with various loads and surface materials, it was found that:

- The grip force would track the load force with a delay of approximately 80ms. Safety margins varied among subjects and loadings.
- The most adroit manipulation was achieved by subjects who used a less stiff grasp. Therefore, choosing the right grasp and finger stiffnesses is important for making the grasp less sensitive to changes in loading.
- Subjects' grasp forces were consistently adjusted on the basis of whichever finger was starting to slip, or the "worst-case-finger".
- When anesthesia was applied to eliminate tactile sensitivity, those subjects who employed a softer grasp configuration were better able to modulate the grasp force. A higher safety margin was necessary.
- Fingertip compliance is a significant fraction of the total finger compliance. The behavior correlates well with the fingertip stiffness models for robotic fingertips proposed in [Cutkosky and Kao 1989].
- When lifting and handling objects, significant moments are exerted about the normal axes of the fingertips. It appears that this phenomenon could be explained by the friction limit surface models proposed in [Kao and Cutkosky 1992]. An interesting question is whether people account for the coupling between frictional moments and tangential forces when setting the grasp force.

3. Hand control is a multi-level supervisory control process. There are muscle reflexes, spinal reflexes and supra-spinal reflexes. The higher levels mediate the performance of the lower. Analogous situations might exist for supervisory control of a slave manipulator equipped with a wide variety of sensors, but limited communications bandwidth with the remote master controller.

4. Muscle tremor may be not merely a symptom of imperfect control, but rather (or perhaps also) a means of continually identifying the dynamic characteristics of the "physical plant" consisting of the muscles, limbs, nerves, etc.

Dynamic tactile sensing for robotic grasp force control

Experimental findings in work at Stanford, Harvard and Umea have provided the basis for a promising approach to grasp force control in telemanipulation. Human subjects control grasp forces and apply manipulation strategies using information from fast-acting (FAI and FAII) tactile afferents which signal events such as the onset of slipping between the fingers and a grasped object. For example, the different phases of a simple grasp-lift-replace manipulation task can clearly be distinguished from the FAII signals. Dynamic tactile sensors developed for robotic and teleoperated hands can provide similar information about the task status. These sensors consist of localized acceleration and stress-rate sensors embedded in the rubber "skin" of a robotic hand. As a consequence, robotic and teleoperated hands can be provided with a similar ability to detect the onset of slipping and other changes in task status.

Recent work at Stanford has focused on sensor-based grasp force control. This work was initiated in February, 1991, during a visit by Edin, Westling and Howe at Stanford. Suggestions from Edin and Westling resulted in reformulations of the robotic skin and improved slip detection strategies. A modified version of the previously developed skin acceleration sensor triggers off "microslips" that precede the onset of gross sliding. A force control algorithm then quickly adjusts the grasp force so that no gross sliding occurs. Using such an approach, it is possible for a robot to maintain control of the grasped object, using the minimum necessary force to prevent slipping. Experiments with a variety of materials, including paper, cloth, and teflon plastic indicate that the sensor is not greatly affected by variations in the material properties of the grasped object and is adequately immune to mechanical vibrations in the manipulator. The experimental results are summarized in [Tremblay *et. al.* 1992]. Ongoing work aims to refine the control strategy so that it is more robust and better able to adapt to a rapid changes in loading and surface conditions.

Dynamic tactile sensing for teleoperation

Although the robotic end-effector can detect such events as the onset of slipping, there remains the problem of conveying this information to human operators in a natural manner. Experiments were therefore conducted in which solenoid actuators in a specially designed object produced small changes in the tangential forces at the fingertips. In trials with human subjects, this object was found to consistently trigger increases in grasp force and stiffness that were essentially indistinguishable from normal human responses to the onset of slipping. Moreover, the human subjects did not demonstrate a tendency to habituate or display a diminished response over repeated trials. The human subjects also reported that it felt as though the object were about to slip out of the grasp [Edin *et. al.* 1991]. These findings led to a set of grasp force control experiments that allowed human subjects to gently grasp objects with teleoperated devices. The experiments were conducted on a new precision force- and position-controlled master and slave hand built at Harvard. This apparatus may also be used to provide precisely controlled stimuli for experiments in human tactile perception. The apparatus was transported to Umea, Sweden for controlled tests with human subjects. The results are summarized in [Howe 1992]. Subjects operating the master manipulator, by pinching the thumb and index finger, were able to precisely manipulate objects at the slave. Information from dynamic tactile sensors on the slave was relayed via a slip tactile display on the master that induced "microslips" at the human end. The human subjects perceived these force redistributions as slips and appropriately increased the grasp force and stiffness to prevent the teleoperated arm from losing its grip. Additional results concerned the design and control

of the system for stable and realistic performance.

Tactile sensor development

The development of tactile sensors has continued at Stanford and Harvard. In particular, improvements have been made to the skin acceleration sensor. Sensor skins with various textures have been cast from several different silicone rubbers and molds. The molds are now created on a computer-controlled milling machine, which makes it easy to experiment with different thicknesses and textures. The skin textures act like human fingerprints to improve grasping and better transmit contact information to the sensors below the skin. The best results have been obtained with vacuum-cast two-part Silastic skins with raised "nibs" (hemispherical projections about 1mm in diameter). Details of tests with various materials are given in [Dorogusker *et. al.* 1992]. Experiments have also been performed with several tactile array sensors, which provide information about the local contact geometry and configuration. Ongoing work concerns the integration of capacitive or Hall-effect array sensors with the skin acceleration and stress-rate sensors to provide a skin with the ability to sense both contact geometry and dynamic contact conditions.

Controller development

Work has begun on the development of new controllers for the robotic and teleoperated equipment. The first objective is to increase the digital servo rate, to improve the fidelity and smoothness of the hybrid force / position control law. The second objective is to increase the utilization of tactile information in the control loop, and to increase the sophistication with which tactile sensors are interpreted.

As a first step, a controller using a digital signal processor (DSP) board has been implemented at Harvard and has obtained a 5Khz servo rate for force control. Descriptions of the approach and the experimental results are given in [Howe 1991]. A similar DSP-based configuration is now being adopted at Stanford. The approach is to use the DSP card as a high-speed, low-level "reflex" controller, receiving supervisory input from the host computer. The exact division of labor between the two processors is a current research topic. Additional areas of work will include the exploration of a variable-impedance control scheme that would be optimally tuned for each operator's inherent impedance; and the establishment of bandwidth requirements for basic manipulation tasks.

Publications from this project

[Edin *et. al.* 1991] B. Edin, R. Howe, G. Westling and M. R. Cutkosky, "Relaying Frictional Information to a Human Teleoperator by Physiological Mechanisms," accepted for publication in the IEEE Transactions on Systems, Man, and Cybernetics, April, 1991.

[Howe and Cutkosky 1991] R. Howe and M. R. Cutkosky, "Dynamic Tactile Sensing: Perception of Fine Surface Features with Stress Rate Sensing," accepted for publication in the IEEE Transactions on Robotics and Automation.

[Cutkosky and Howe 1990] M.R. Cutkosky and R.D. Howe, "Human Grasp Choice and Robotic Grasp Analysis," Chapter 1, Dextrous Robot Hands, S.T. Venkataraman and T. Iberall, eds., Springer-Verlag, 1990.

[Howe and Cutkosky 1990] R. Howe and M.R. Cutkosky, "Integrating Tactile Sensing with Control for Dextrous Manipulation," Proceedings of the IEEE International Symposium on Intelligent Motion Control, 1990.

[Cutkosky 1992] M.R. Cutkosky, "Modeling and Sensing Finger/Object Contacts for Dextrous Manipulation," IEEE workshop on "Approaching and Grasping Strategies for unknown objects," May 15, 1992.

[Howe and Cutkosky 1992] R. D. Howe and M. R. Cutkosky, "Touch Sensing for Dextrous Manipulation and Exploration," The Robotics Review 2, O. Khatib, J. Craig and T. Lozano-Perez, eds., M.I.T. Press, Cambridge, MA, 1992, pp. 55-112.

[Howe 1992] R. Howe, "A Force-Reflecting Teleoperated Hand System for the Study of Tactile Sensing in Precision Manipulation," Proceedings of the IEEE International Conference on Robotics and Automation, Nice, May 1992, pp. 1321-1326.

[Tremblay *et. al.* 1992] M. Tremblay, W. Packard, M. Cutkosky, "Utilizing Sensed Incipient Slip Signals for Grasp Force Control," Proceedings of the 1992 US-Japan Symposium on Flexible Automation.

[Dorogusker *et. al.* 1992] J. Dorogusker, E. Ducceschi, S. Nguyen, "Fingertip Skin Design for a Tactile Sensing Robotic Finger," results of undergraduate student project on selection of skin materials for dynamic tactile sensing.

Previous Correspondence

[Cutkosky 1990a] A detailed information exchange was conducted to determine how theories from robotics can be applied to physiological experiments with human subjects and how recent findings in physiology can be used to guide the development of advanced robotic/teleoperated systems. A document summarizing the results of this exchange was compiled on October 4, 1990 and transmitted to Dr. T. McMullen.

[Cutkosky 1990b] A set of preliminary experiments was conducted at Stanford involving grasp force control mediated by dynamic tactile sensing. These experiments were motivated by observa-

tions of FAI and FAII tactile receptor outputs during manipulation tasks with human subjects at Umea and by the availability of new dynamic tactile sensors developed by R. Howe. Parallel experiments at Umea focused on the artificial elicitation of increases in grasp force by human subjects. Preliminary results from these experiments were outlined in a status report sent to Drs. Hawkins and McMullen on December 12, 1990. Further results are described in [Edin *et. al.* 1991].

[Cutkosky 1992a] Recent work in the development of new tactile sensors, development of a new controller, and dynamic tactile sensor-based grasp force control in both robotic manipulation and teleoperation was described in a progress report sent to Drs. Hawkins and McMullen on February 18, 1992.

Additional References

[Cutkosky and Kao 1989] M.R. Cutkosky and I. Kao, "Computing and Controlling the Compliance of a Robotic Grasp," IEEE Transactions on Robotics and Automation, Vol. 5, No. 2, April, 1989, pp. 151-165.

[Kao and Cutkosky 1992] I. Kao and M. R. Cutkosky, "Quasistatic Manipulation with Compliance and Sliding," The International Journal of Robotics Research, Vol. 11, No. 1., 1992, pp. 20-40.

Student Theses

P. Akella, "Contact Mechanics and the Dynamics of Manipulation," Ph.D. Thesis, Stanford University, August 1992.

Interactions with industry

Several interactions have taken place with Dr. Donald Gorman of the Lockheed robotics group, resulting in a proposal "Object identification using tactile sensing," submitted to J. Granet of OPNAV (LMSC P000066, Nov. 8, 1991).

Hardware and software prototypes developed

- Skin acceleration sensor (described in detail in [Howe 1990] and [Tremblay *et. al.* 1992]) for detecting changes in contact status.
- stress rate sensor (described in detail in [Howe 1990] and [Howe and Cutkosky 1991]) for measuring fine surface features.
- Tactile slip display (described in detail in [Edin *et. al.* 1991] and [Howe 1992]) for telemanipulation.
- Force reflecting teleoperated hand system (described in detail in [Howe 1992]) for telemanipulation.
- Grasp force control algorithm based on sensing incipient slip (described in detail in [Tremblay *et. al.* 1992])

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
Aug 4, 1992

3. REPORT TYPE AND DATES COVERED
Final

4. TITLE AND SUBTITLE
Tactile Sensing and Control in Humans, and Robotic Teleoperated Systems

5. FUNDING NUMBERS
N-00014-90-J-4014-P01

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Perceptual Science Program (1142PS)
Office of Naval Research
800 N. Quincy Street
Arlington, VA 22217-5000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release. Distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

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14. SUBJECT TERMS
Tactile sensing, robotics, physiology, dextrous manipulation, teleoperation.

15. NUMBER OF PAGES
8 plus attachments

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT